Beam-Based Alignment in terms of 1:1 Correction and Kick Minimization Algorithms in Proton Linac

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Objectives

- In multi-MW ion linac, like Project-X, typical misalignment of magnets of higher than ~100-200 μm leads unacceptable particle losses (limit ~1W/m), thus need to apply correction to align SC linac to required level.
- Only few existing codes (TRACK) have internal built-in correction scheme. Implementation of other schemes is difficult.
- Our approach is to build correction algorithms outside of the code and use tracking code to provide transfer matrices and needed beam position information. It gives us flexibility for study misalignment and errors and correction. Any tracking code (ASTRA, TraceWin, etc) can be used in this approach.

First step – 1:1 correction

- 1:1 correction algorithm

  One of the ways to make the beam close to a straight line is to force it to pass through all BPM centers.

- This procedure is possible if BPMs are precisely aligned along the reference axis.
- If the BPM centers are misaligned from the reference axis one can use some additional techniques for adjusting linac: Dispersion Free Steering, Ballistic Alignment and Kick Minimization, for example.

Kick Minimization

- In SC cryomodule hard to control misalignment of elements (incl. BPM) better than 300µm. Nevertheless, if one can align BPM to magnet better than that, it can be used in alignment KM algorithm.
- There are some special techniques that allow to align BPM with respect to quads, for example preliminary mechanical alignment before installation (align and fix) or quad shunting. After these procedures BPMs are aligned to centers of magnetic lenses pretty good .
- Kick minimization algorithm attempts to make use of this additional information.
- For a quad with nonzero BPM reading b, the beam is kicked by the quad.

$$\Theta_{quad} = \frac{1}{f} b,\ \Theta_{cor} \approx -\Theta_{quad},\ b + \Theta_{cor} f \approx 0$$

- If the corrector gives an **opposite kick** the beam will pass the quadrupole **unkicked**. (P. Tenenbaum)
- The condition of kick minimization aligns the beam in a straight line. But the direction of this line may be wrong (with respect to the reference axis). Therefore we still need to use 1:1 algorithm.
- Thus, our goal is to find a set of correctors that satisfies as good as possible simultaneously two conditions: 1:1 and kick minimization.

Basic Equations (1)

- Let's consider a vector of BPMs readings as a function of a vector of correctors $\vec{b} = \vec{b}(\vec{\theta})$
- Linearized equations are

$$\begin{pmatrix} b_0 \\ b_1 \\ \dots \\ b_n \end{pmatrix} = \begin{pmatrix} b_0^0 \\ b_1^0 \\ \dots \\ b_n^0 \end{pmatrix} + \hat{M} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \dots \\ \theta_n \end{pmatrix}$$

where M is a response matrix of the system.

- In 1:1 correction we want to obtain zero values of BPMs readings, that is

$$-\begin{pmatrix} b_0^0 \\ b_1^0 \\ \dots \\ b_n^0 \end{pmatrix} = \hat{M} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \dots \\ \theta_n \end{pmatrix}$$

Basic equations (2)

- In Kick Minimization algorithm we have a relation between each pair of BPM and corrector : $\theta_k = -\frac{b_k}{f_k}$
- We can rewrite linearized equations $\vec{b} = \vec{b}(\vec{\theta})$ as

$$-b_k^0 = \sum_j M_{kj}\theta_j + f\theta_k$$

- or in matrix representation

$$-\begin{pmatrix} b_0^0 \\ b_1^0 \\ \dots \\ b_n^0 \end{pmatrix} = \hat{N} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \dots \\ \theta_n \end{pmatrix}$$

- where

$$N_{ij} = \begin{cases} M_{ij} + f, & i = j \\ M_{ij}, & i \neq j \end{cases}$$

Basic equations (3)

- To minimize kicks of quadrupoles and keep the beam close to the reference axis we have to balance these two techniques and solve two sets of equation together with some weight ω.

$$-\begin{pmatrix} b_0^0 \\ b_1^0 \\ \dots \\ b_n^0 \\ \omega b_0^0 \\ \omega b_1^0 \\ \dots \\ \omega b_n^0 \end{pmatrix} = \begin{pmatrix} M \\ \omega N \end{pmatrix} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \dots \\ \theta_n \end{pmatrix}$$

The weight should be set such that two techniques give the same impact to χ^2.

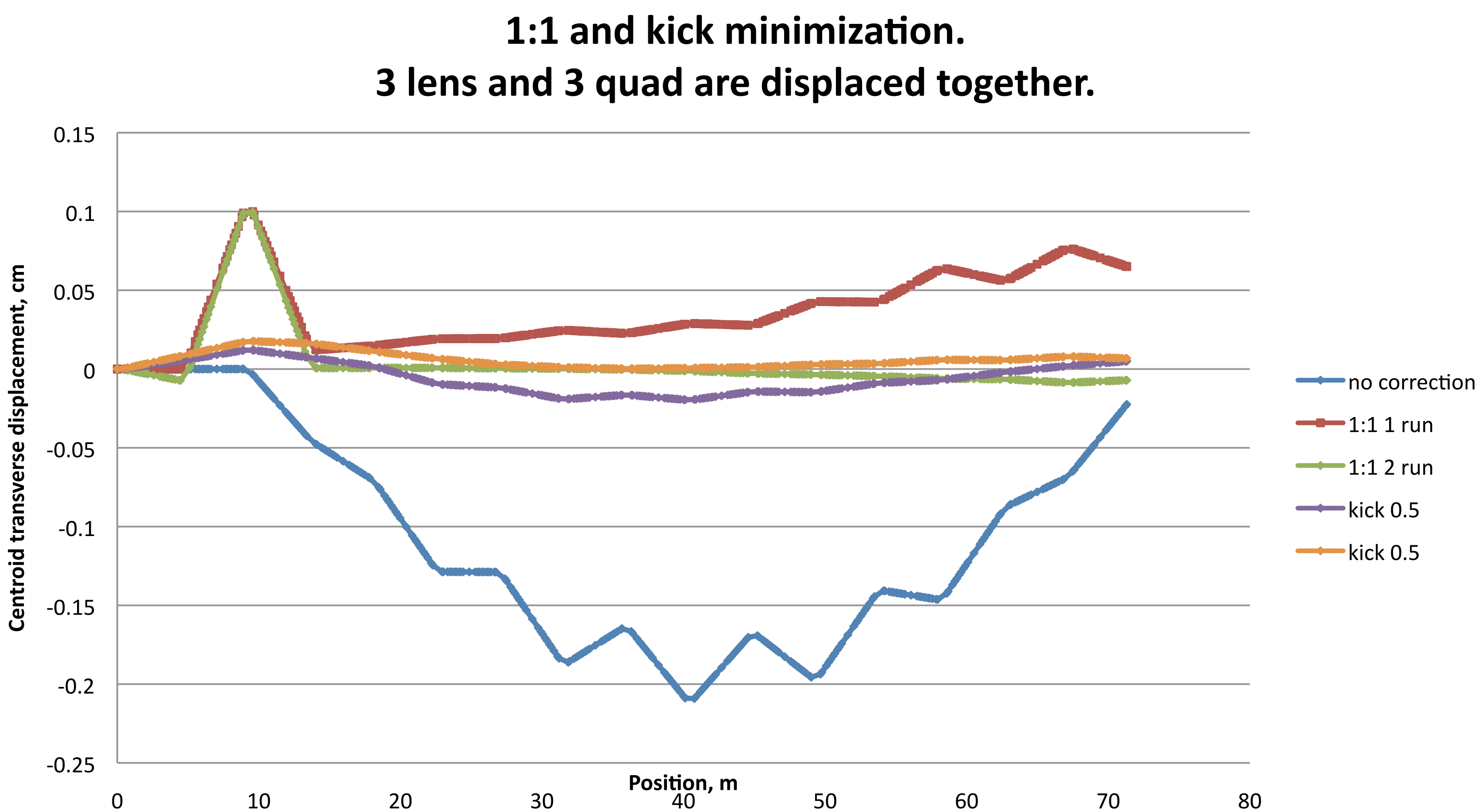
Goals

1. Implement 1:1 correction and Kick Minimizations techniques in the FODO lattice.
2. Study losses of particles.

Simulations in TRACKv39

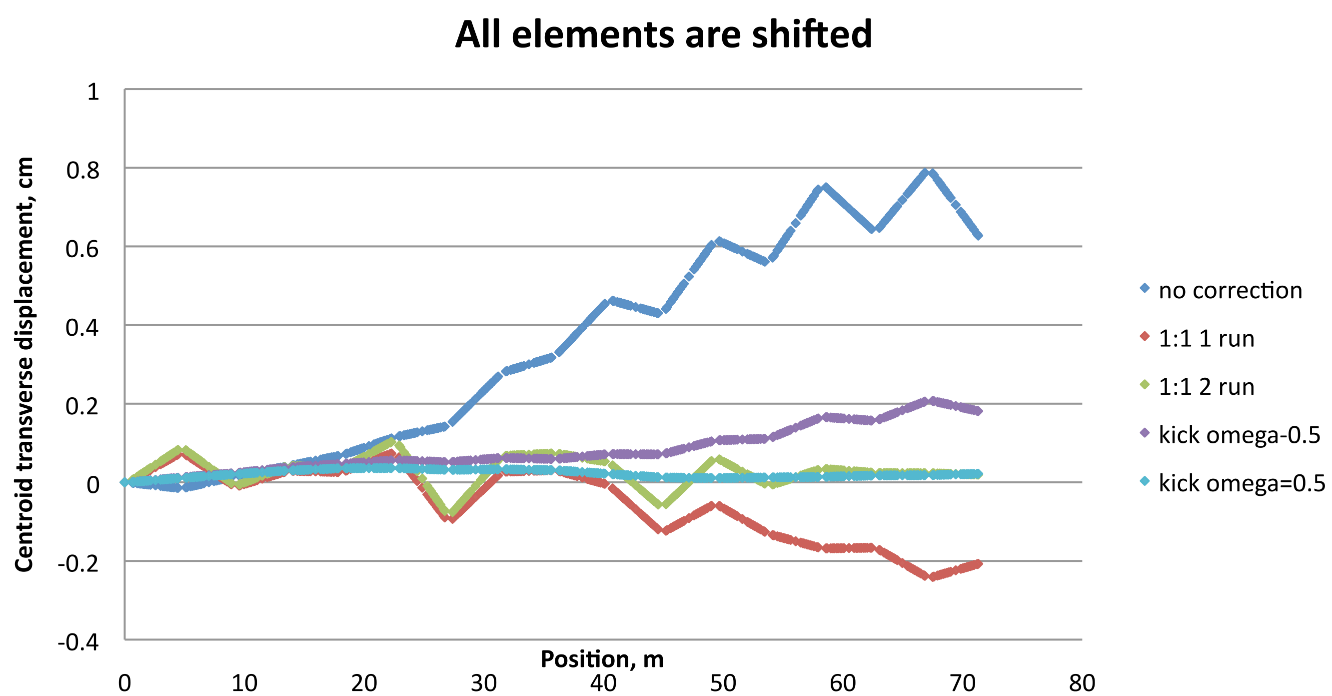
1. Determining of transfer matrixes and the response matrix of the lattice by means of TRACKv39.
2. Tracking with initial displacements of elements, extracting BPMs readings.
3. Finding a set of correctors for extracted BPMs readings (using Python scripts and Octave).
4. Tracking again, taking into account the set of correctors.

Results



1:1 and kick minimization.
3 lens and 3 quad are displaced together.
Centroid transverse displacement, cm
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
Position, m
0
10
20
30
40
50
60
70
80
no correction
1:1 1 run
1:1 2 run
kick 0.5
kick 0.5

Results



BPMs are close to the centers of quads, but there is an error in fixing σ=0.02 cm.
Error in quad position with respect to reference axis is σ=0.2 cm.